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FIREFIGHTING AND EMERGENCY RESPONSE STUDY OF ADVANCED COMPOSITES AIRCRAFT

Objective 2: Firefighting Effectiveness of Technologies and Agents on Composite Aircraft Fires

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14. ABSTRACT Over the past few years, the amount of composite material used in aircraft has greatly increased due to its inherent light weight and high strength. However, recent mishaps involving composite aircraft call into question the ability to extinguish composite fires with the same effectiveness as current methods used for aluminum-skinned aircraft. To this end, a series of medium-scale fire experiments were performed on aerospace composite materials to determine the capability of various fire suppression technologies (e.g., air-aspirated, compressed-air foam, ultra-high pressure) and agents (e.g., aqueous film-forming foam, film-forming fluoroprotein, Class A foam, dry chemical, and gels) to extinguish composite fires. In each experiment, two carbon fiber bismaleimide panels were placed nearly parallel to each other in a steel frame over a pool of jet fuel. The pool was ignited and allowed to burn for a predetermined amount of time, after which a firefighter extinguished the pool fire followed by the composite fire. Time, temperature, heat flux, and video were recorded throughout the process. Results will aid in decisions being made for composite aircraft fire extinguishment.					
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1. SUMMARY

1.1. Background

Recent improvements in materials technologies have prompted the use of composites as aerospace materials in lieu of conventional aluminum-skins. Composites are lightweight, high-strength materials that allow for faster speeds and larger payloads on aircraft. The amount of composite materials has increased dramatically over the last few decades^[1]. For example, the B-2, F-22, Osprey, and upcoming F-35 military aircraft as well as Airbus A-380 and Boeing 787 commercial aircraft contain significant amounts of composites.

Although there are advantages to using these lightweight composites, their thermal and structural behaviors in a fire environment differ substantially from those of metal materials. In multiple instances, after visible extinguishment of the aircraft by firefighters, smoldering combustion continued within the carbon fibers of the porous, stratified composite structure of the aircraft. This internal heat within the burnt composites allowed for reignition of the volatiles, requiring application of additional agent to the fire. One specific instance showed that firefighters used approximately 10 times the minimum agent amount to completely extinguish the composite aircraft^[2]; this is the amount required to be on-hand for a size-specific aircraft fire.

Recent fire incidents involving military composite aircraft have forced consideration of new concepts of operation for composite aircraft firefighting. The Air Force Civil Engineer Support Agency (AFCESA) and Air Combat Command (ACC) tasked the Air Force Research Laboratory (AFRL) with answering four key questions relating to composite firefighting: (1) How do composite materials react to small fires (e.g., engine nacelle) and when does significant damage occur to surrounding material? (2) What are the best application methods and agents to effectively extinguish a composite fire? (3) What are the best tools for penetrating and overhauling composites? (4) What are the best methods to decontaminate equipment after exposure to composite fire environments? This report focuses on the second question—which methods and agents are the most effective in extinguishing composite materials in fire.

1.2. Scope

This report summarizes experiments performed on intermediate-sized composite panels to determine which particular agent and application technology would be best suited to extinguish a composite fire. Findings were based on the time for extinguishment by the suppression system and agents and also ability to inhibit reignition of the liquid and/or solid fuel based on temperatures on and near the composite panels. A standard experimental apparatus was designed and built to simulate a composite fire above a pool of JP-8 fuel. An adaptation of a standardized military specification^[3] (MIL-SPEC) was used to determine pre-burn, extinguishment, and subsequent reignition of the composite material.

Commercial technologies (air-aspirated [AA], non-air-aspirated [NAA], compressed-air foam [CAF], ultra-high pressure [UHP]) and agents (aqueous film-forming foam [AFFF], film-forming fluoroprotein [FFFP], Class A foam, potassium bicarbonate [PKP], and fire suppression hydrogel [HG]) that are currently available were used in these experiments. Features of the composite materials, such as resins, surfaces, and/or physical properties, were not variables in

this experiment. The same standard composite material was used for each experiment for repeatability. Additional small-scale experiments were also performed to determine cooling effectiveness of various commercial agents on composite coupons exposed to uniform heating with a propane torch.

1.3. Conclusions

Medium-scale tests showed AA and CAF systems to be more effective than the UHP system, which was more effective than the NAA system. The momentum from UHP created a better cooling environment than AA and CAF, but all the agent could not be effectively applied to the test materials, making a side-by-side comparison difficult in the medium-scale tests. PKP had the fastest extinguishment, where typical water-based agents (AFFF, FFFP, and Class A) were similar in performance. However, PKP did not cool the composite, allowing the hot material to reignite after initial extinguishment. HG cooled the composite, but disturbed the pool fire below, allowing the JP-8 fuel to reignite.

Small-scale tests showed that HG had a longer cooling effect than other agents. Although AFFF initially cooled the sample, due to evaporation and water dripping from the composite it could not maintain cooling. Samples to which PKP was applied showed poorer cooling than samples with no agent applied, as evidenced by PKP's caking onto the surface of the composite, thereby creating an insulating layer that inhibited cooling.

2. INTRODUCTION

2.1. Background

Recent improvements in materials technologies have made possible the use of composites as aerospace materials, replacing conventional aluminum-skinned aircraft. Composites are lightweight, high-strength materials that allow for faster speeds and larger payloads on aircraft. The amount of composite materials has increased dramatically over the last few decades^[1] (Table 1). For example, the B-2, F-22, Osprey, and upcoming F-35 military aircraft as well as the Airbus A-380 and Boeing 787 commercial aircraft contain significant amounts of composites.

Table 1. Amount of Composite Material in Modern-day Aircraft

First Flight	Aircraft	Department	Percent Composite	Composite Weight (1000 kg)
1962	CH-46E	USN	22	1.4
1972	F-15	USAF	2	0.5
1974	H-53	USN	10	1.4
	F-16	USAF	13	0.9
	H-60 Blackhawk		17	0.9
1976	Harrier GR-5	RAF	32	1.8
1978	F/A-18	USN	10	0.9
	AV-8B Harrier	USN	26	1.8
	H-60 Seahawk		17	1.4
1979	H-60 Seahawk	USN	17	1.4
1987	A-320	Commercial	16	6.8
1989	B-2	USAF	37	26.4
	V-22 Osprey	USN/USAF	70	10.5
1990	MD-11	Commercial	30	38.6
1991	C-17	USAF	8	10.5
1994	Eurofighter	NATO	70	3.6
1997	F-22	USAF	38	7.7
2005	A-380	Commercial	20	55.5
2009	Boeing 787		50	50.9

Composite-skinned aircraft burn inherently differently from aluminum-skinned aircraft. Aerospace composites consist of fibers and resins, of which 25–50 wt% of the material can oxidize. The resin matrix will begin to pyrolyze at 200–500 °C, which varies greatly by matrix type. Permanent thermal damage can occur after the matrix reaches its glass transition temperature (T_g). Also, the fibers for some aerospace composites (e.g., carbon) can undergo char oxidation at higher temperatures (1200–2000 °C). The composite material is inherently a good insulator, which can be both advantageous and disadvantageous: advantageous for fire protection because it can resist heat from nearby sources, disadvantageous for fire suppression because once the material has heated up, it cannot easily dissipate heat to adequately cool the material. On the other hand, aluminum will melt at somewhat higher temperatures than which most resins burn (650 °C vs. 200–500 °C). Also, because aluminum is conductive, it allows the material to dissipate heat and cool after subjection to fire.

2.2. Mishap History

Recent Air Force fire incidents involving composite aircraft show the difficulties in fighting fully involved composite fires. In September 1997, a section of the left wing of an F-117 sheared off during an air show near Baltimore, MD, and the aircraft crashed into a residential area. The fire was fueled by JP-8 fuel, construction debris, and airplane wreckage. Local firefighters responded and extinguished the fire, after which the wreckage continued to smolder for hours. Firefighters called to the scene reported respiratory distress for weeks following the incident.

Another incident occurred in December 2004 at Nellis AFB, NV, involving an F-22 that had crashed near the runway (Fig. 1). Air Force firefighters responding to the crash, fought the composite fire for several hours, during which time the smoldering composite material reignited and flaming combustion of the aircraft recommenced. The firefighters found it difficult to cool the inner portions of the wreckage. Also, the material was observed to off-gas for several months after the crash.

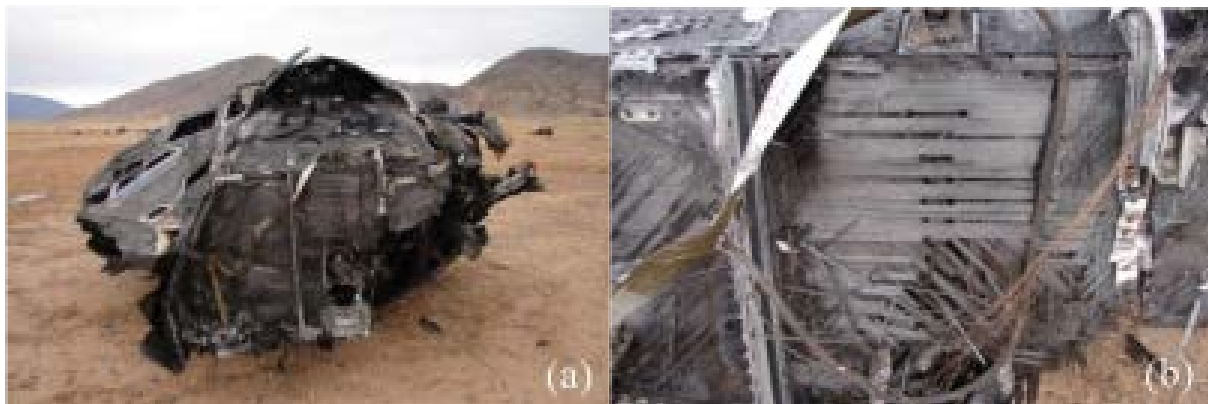


Figure 1. (a) Portion of Wrecked F-22 Cockpit at Nellis AFB; (b) Close-up Showing Delaminated Composite Materials

Finally, an incident February 2008 at Anderson AFB, Guam, involved a B-2 that crashed directly after takeoff just off the runway. By the time Air Force firefighters responded to the crash, the entire aircraft was engulfed in burning JP-8. As with previous incidents, the firefighters had difficulty reaching hidden areas. They also observed reignition of composite materials following extinguishment. All in all extinguishing this composite fire required six hours. The firefighting effort (Fig. 2) used 303,000 L (80,000 gal) of water and AFFF, ten times the minimum required amount prescribed^[2] by NFPA 403 to be on hand for emergency responders for an aircraft of its size. Smoldering combustion was observed for days following the incident. Also, all materials with permeable surfaces (bunker gear, hoses, etc.) were discarded, since the amount of composite fiber contamination and the potential hazards to the fire crew were unknown.



Figure 2. (a,b,c) Various Views of Firefighting Efforts on B-2 Crash at Anderson AFB

These incidents have forced consideration of new concepts of operation for composite aircraft firefighting. AFCESA and ACC requested that AFRL answer four key questions relating composite firefighting: (1) How do composite materials react to small fires (e.g. engine nacelle) and when does significant damage occur to surrounding material? (2) What are the best application methods and agents to effectively extinguish a composite fire? (3) What are the best tools for penetrating and overhauling composites? (4) What are the best methods to decontaminate equipment after exposure to composite fire environments? This paper focuses on the second question—which methods and agents are the most effective in extinguishing composite materials in fire.

3. METHODS, ASSUMPTIONS AND PROCEDURES

The experiments were designed to simulate realistic, robust live-fire conditions using aerospace-grade composite materials. The overall experimental setup encouraged reignition of the composite materials after extinguishment. A standardized test fire was used for all suppression experiments. This standardized test was based on the MIL-SPEC^[3] MIL-F-24835F for AFFF, with modifications to include the composite materials. In addition to these intermediate-scale tests, a series of small-scale experiments were performed on smaller panels to determine the cooling effects of various agents.

3.1. Intermediate-Scale Experiments

These intermediate-scale composite tests used a steel pan 1.8 m (6 ft) in diameter and 10.2 cm (4 in) deep filled with water (189 L [50 gal]) and JP-8 fuel (76 L [20 gal]). The composite materials were placed above the pool in a steel frame. The fuel was ignited and allowed to burn for a predetermined amount of time (pre-burn), after which a firefighter applied agent to the pool fire. As soon as the pool was extinguished, agent application was directed to the composite fire until extinguishment. The baseline technology used for all preliminary tests was an air-aspirated (AA) nozzle and the baseline agent was MIL-SPEC-compliant AFFF.

3.1.1. Composite Material Setup

Two quasi-parallel panels (61 cm × 91 cm × 1.6 mm [2 ft × 3 ft × $\frac{1}{16}$ in]) were placed in a steel fixture that allowed stress to be applied in a four-point bend similar to ASTM standards^[4], one panel in the vertical direction, one in the horizontal direction, where the center of the each panel was displaced about 3.8 cm (1.5 in) (Fig. 3a). Red bars indicate pressure on the inside of the chimney pushing outward, while blue bars indicate pressure on the outside of the chimney pushing inward. The fixture was designed in this manner to simulate loads that the composite material (e.g., fuselage) would experience during fire, which can alter the way the composite behaves (e.g., delaminates) as opposed to stress-free conditions. Also, the two parallel panels, separated by 14 cm (5.5 in) without bending, allowed for radiative heating from one to the other, which created a fire more difficult to suppress.

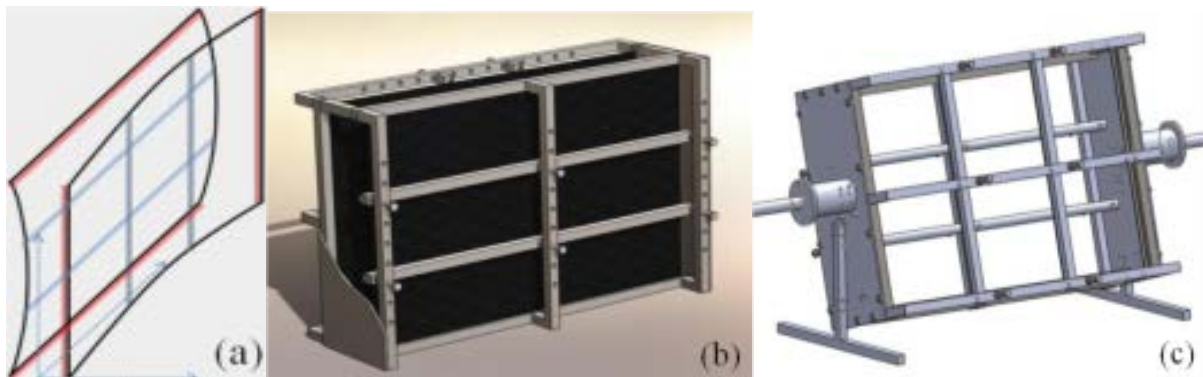


Figure 3. (a) Schematic Showing Quasi-parallel Panels and Four-point Bend Placed in the Horizontal and Vertical Directions; (b) Diagram Showing Steel Fixture and Composite Panels; (c) Diagram Showing Instrumentation and Tiltability of Frame

Actual tests were performed using an aerospace-grade carbon bismaleimide (BMI) laminate (IM7/Cytec 5250-4) with a 0/90 layup. Preliminary testing was done with a carbon epoxy (IM3/Cytec 997) laminate with a 0/90 layup, which was slightly thicker (3.2 mm [$\frac{1}{8}$ in]) than the BMI panels, mainly to determine the length of pre-burn and to determine the best firefighting technique for extinguishing the fire. Two other tests were also run with plywood panels with thicknesses of 1.6 mm ($\frac{1}{16}$ in) and 9.5 mm ($\frac{3}{8}$ in), also for the purpose of familiarizing the firefighter with the equipment.

3.1.2. Fixture Setup

In addition to four-point bends in each direction, the fixture had steel plates on the sides of the composite panels, which created a vertical duct or chimney-like cavity (Figs. 3b and c). The fixture was tilted $\pm 15^\circ$, which allowed the lower end of one composite panel to dip into the fuel and created a wicking effect that transported fuel from the pool into the interior of the composite panel. Also, the tilt created a gap (5 cm [2 in]) between the upward-tilted panel and the fuel surface. This gap allowed air to flow through the cavity, which created convective heating in the interior of the duct.

This fixture was instrumented with Medtherm 96-30T-30RP(ZnSe)-120-21746 Schmidt–Boelter heat flux sensors to measure the heat flux within the cavity (Fig. 3c), with both radiant and total flux components. A nitrogen purge was blown onto the surface of the total sensor to keep soot from forming on the surface of the sensor. These sensors were positioned midway (vertically and horizontally) on the steel plates that formed the sides of the cavity. Located 2.5 cm (1 in) above the heat flux sensors were ports from which thermocouples extended 12.7 cm (5 in) into the interior of the cavity. The data were acquired via a PXI/SCXI National Instruments chassis at a rate of 1 Hz. Results are reported as an average of the two measurements (e.g., two heat flux measurements yield an average heat flux in the cavity). The radiative and convective heating, as well as the addition of volatile fuel via the wicking effect, allowed for a high-intensity, robust fire that was subject to the possibility of reignition after extinguishment.

3.1.3. Test Procedure

Steps to the procedure were as follows:

- (1) The JP-8 fuel was ignited with a propane torch.
- (2) The firefighter waited the pre-burn duration. From preliminary experiments using carbon/epoxy panels, this time was determined to be 45 s. (A JP-8 pool without composites and fixture typically reached steady burning conditions in 20–25 s. Therefore, the remaining 20–25 s allowed the pool fire to heat and burn the composite material. Further discussion of pre-burn duration is found in section 4.1.1.)
- (3) The firefighter began extinguishing the pool fire, which typically required about 30 s. A foam blanket was formed using AFFF until the pool was 95–100% extinguished. This time was defined as the pool extinguishment time.
- (4) Upon extinguishment of the pool, the firefighter began applying agent to the burning composite materials. When using an agent other than AFFF, the firefighter would switch

nozzles (a separate system [tank, hose, and nozzle] already prepared) to fight the composite fire with the secondary agent. When using AFFF, the firefighter would simply begin applying AFFF to the composites with the same nozzle. This time required to fight the composite fire was defined as the *composite extinguishment time*.

- (5) Once complete extinguishment was detected by the firefighter, agent application was stopped and the test panel was observed for possible reignition. Total extinguishment time was the time between initial agent application and the time when flames (from both pool and composite) were not visible; this time included reignition if it occurred.

3.1.4. Design of Experiments

A design of experiments was developed to determine which methods of application and agent were most effective in extinguishing the composite fire. First, because the test fixture could be tilted, it was necessary to determine the effect of this tilt on the burning and particularly the extinguishment of the composites. These experiments included replications with the fixture tilted in positive (horizontally stressed panel dipped in fuel) and negative (vertically stressed panel dipped in fuel) directions. The baseline conditions were used in all tests (i.e., AA nozzle with AFFF as the agent). Data were then analyzed to determine which tilt angle (if any) created the more difficult fire to extinguish. The same angle was then used in all subsequent tests.

After tilt effects were determined, the type of application technology was varied (with replications), maintaining AFFF as the baseline agent as well as maintaining the same flow rate (7.6 L/min [2 gpm]). The various technologies used were AA, NAA, CAF and UHP. Each technology (delivering AFFF agent) was applied to the pool first, then to the composite material. Data were analyzed to determine which technology most effectively extinguished the prescribed test fire. This application technology was then selected for subsequent agent tests.

Once technology effects were determined, the type of agent applied to the composite fire was varied. Because each agent performed differently in extinguishing Class B (JP-8) fires and to maintain consistency, AFFF was used to extinguish the pool fire first, then the firefighter switched to the secondary agent to extinguish the fire from the composite sample. Secondary agents used were AFFF, film-forming fluoroprotein (FFFP), a Class A foam (Class A), potassium bicarbonate dry chemical (PKP), and a hydrogel (HG). Each group of experiments included at least four replications of each angle, technology and agent.

3.1.5. Flow System Characterization

The standard AA system used in the MIL-SPEC^[3] experiments was a 76-L (20-gal) tank filled with a batch of foam (3% AFFF-MS [military specification]) and water; other water-based agents could also be used in this system. The tank was pressurized to the desired level (690 kPa, 100 psi), and the water-foam mixture traveled through a 2.5-cm (1-in) diameter hose to the nozzle. The nozzle design (Fig. 4) was specified in the MIL-SPEC^[3], which includes holes near the nozzle exit that aspirate the foam. The NAA system was identical to the AA system, except that the aspiration holes in the nozzle were plugged. A Tri-max 30 unit, a system that compresses air and creates the foam in the unit upstream of the nozzle, was used for the CAF application. The same hose and nozzle in the AA system were used for the CAF experiments. The UHP system was custom-designed for lower flow rates (3.8–22.7 L/min [1–6 gpm]), and could deliver the outlet stream at significant pressure (0–20.9 MPa [0–3000 psi]). This unit consisted of a

premixed tank that fed into a centrifugal charge pump (Model 45 CAT Plunger) controlled by a variable voltage signal. This pump supplied head pressure to the main piston pump, routing agent to a handheld nozzle (Stoneage). System designations and corresponding foam characteristics for all technologies using 3% AFFF are shown in Table 2.

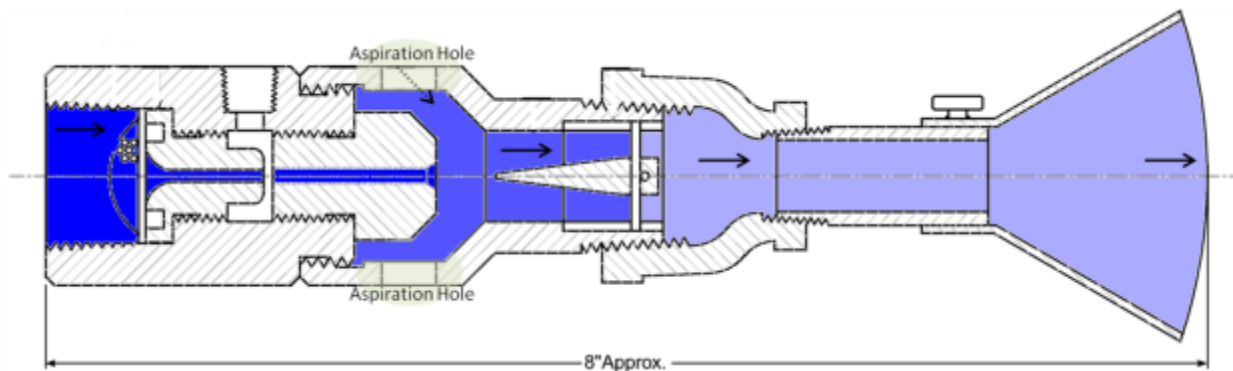


Figure 4. Schematic of Standard Nozzle Used for Experiments

Table 2. Application Technologies Used for Experiments and 3% AFFF Characteristics for Each Technology

Extinguishing System	Pressure (kPa [psi])	Flow Rate (L/min [gpm])	Foam Expansion	Drainage Time (min)
Air-aspirated (AA)	690 [100]	7.6 [2.0]	4.2	4.4
Non-air-aspirated (NAA)	690 [100]	7.6 [2.0]	1.7	5.0
Compressed air foam (CAF)	2400 [350]	7.6 [2.0]	8.1	6.4
Ultra-high pressure (UHP)	6900 [1000]	7.6 [2.0]	2.4	2.9

Chemguard AFFF at 3% (by volume), Chemguard FFFP at 3%, Chemguard Class A at 0.5%, Chemguard PKP, and Earthclean TetraKO HG were used to extinguish fires in the composite samples. Water-based agents excluding HG were prepared by mixing 38-L (10-gal) batches of water with the appropriate amount of foam concentrate in solution; this amount was sufficient to ensure that the pressure and flow rate would remain constant throughout agent application. PKP was dispensed from a pressurized tank (690 kPa [100 psi]) at a rate whose mass flow rates (6.8 kg/min [15 lb/min] for powder corresponded to 7.6 L/min [2 gpm] \approx 7.6 kg/min [16.7 lb/min] for water). These flow rates linearly were assumed to roughly correspond to full-scale systems delivering both powder- and water-component extinguishants^[5]. A cylindrical metal disk with a 3-mm (0.12-in) diameter hole was inserted into a standard extinguishing nozzle to obtain the desired flow rate. To obtain a gel-like consistency for the HG, 54 g (1.9 oz) of powder was slowly added to 7.6 L (2 gal) of water while the solution was continually mixed. Multiple batches were made to yield approximately 38 L (10 gal) of gel to be used in the standard tank.

3.2. Small-Scale Experiments

A propane torch was used to heat the composite samples for a predetermined amount of time in the small-scale composite tests. The heat source was removed, and the sample was allowed to

cool at (a) room temperature or (b) with a layer of applied agent. This series of experiments was done to determine the cooling effectiveness of various types of agents on composite samples.

3.2.1. Experimental Apparatus

A single 10.2-cm \times 10.2-cm \times 1.6-mm (4-in \times 4-in \times $\frac{1}{16}$ -in) BMI laminate (same material as described in section 3.1.1) was placed in a sample holder that allowed for compressive bending of the sample. The sample holder consisted of two steel C-clamps (Fig. 5) with a 2.4-mm ($\frac{3}{32}$ -in) wide groove in each clamp head to allow space for the composite sample edge to sit. The clamp head was placed 5.1 cm (2 in) from the other clamp head, centering the composite sample. The clamp body was angled away from the other clamp, so the back side of the composite sample could be viewed completely. With the compressive bending, the center of the sample was displaced approximately 1 cm (0.4 in).

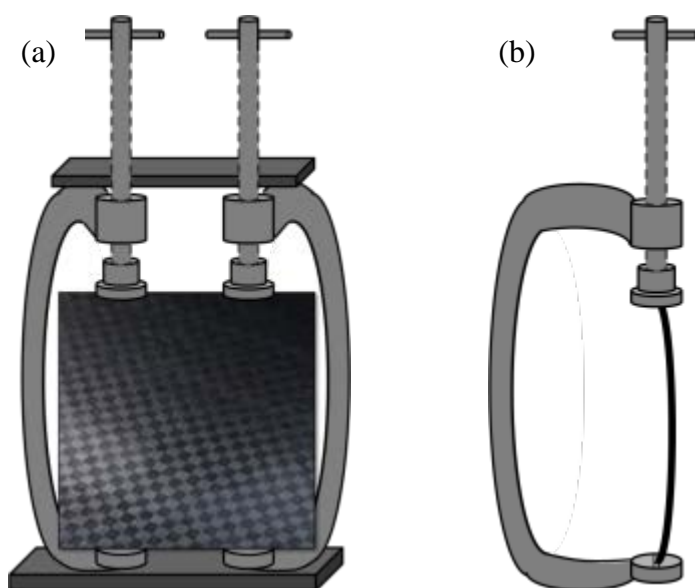


Figure 5. Schematic of Small-scale Apparatus; (a) Front View and (b) Side View

3.2.2. Test Procedure

With the composite sample in place, a propane torch with a temperature of 1200 °C and a localized heat flux of 115 kW/m² was placed approximately 3.8 cm (1.5 in) from the sample with the flame directly impinging (normal to) the sample. A flame impingement time of 1 min was used to heat the sample to a relatively constant temperature. Once the sample reached thermal equilibrium, verified by measurement with an infrared (IR) camera, the propane source was removed and either the composite was allowed to cool in ambient air, or a stream of agent was applied to the sample within 1 s, which was then allowed to cool.

Four different cooling agents were applied after initial pre-burn: (1) ambient air cooling only, (2) AFFF (main water-based agent), (3) PKP (dry agent), and (4) HG (water-based agent that sticks to the solid). The application rate of the agent was the same as those used in section 3.1, 7.6 L/min (2 gpm). The firefighter passed over the sample once with flowing agent, estimating that the nozzle was moving at approximately 0.15 m/s (0.5 ft/s) at a distance of 0.3 m (1 ft) from the sample, to apply approximately 60 g (or 60 mL for water-based agents) of agent to the solid,

though the amount of agent that adhered to the surface varied due to its viscosity. The average back side temperature of each sample was monitored using a FLIR SC660 IR camera at a rate of 0.5 Hz, measuring a spectral range of 7.5–13 μm and, assuming an emissivity of 0.9 (typical for most non-metallic surfaces), a temperature range of 0–500 °C. The back side of the sample did not experience the changing effects of the propane flame and agent application, which could have affected the spectral emission and altered the temperature measurement. Five replications for each case were performed.

4. RESULTS AND DISCUSSION

The following sections discuss the burning and extinguishment/cooling characteristics of the composite fire in both the intermediate- and small-scale tests.

4.1. Intermediate-Scale

A typical intermediate-scale experiment demonstrated a variety of phenomena associated with actual composite material fires. Because the composite laminates were under load, the panels buckled and fell from the four-point bend of the steel fixture. Delamination also occurred, which caused expansion of the panel and further inhibited cooling of the composite material (Fig. 6). Also, audible crackling was heard, due to volatiles escaping from the interior of the thin panels and the breaking down of carbon fibers.

Because the resin pyrolyzes and burns from the composite, most of the fiber remains after burning. This effect was greatest when the pre-burn time of the pool fire before extinguishment was excessive (e.g., greater than 2 min). It was also observed that some residue from the composite resolidified once exposed to a heat sink. This occurred mainly near the bottom of the composite, where resin dripped down the face, hit the pool of water beneath the surface of the fire, and resolidified on the metal fixture and pan (Fig. 7a). This resolidified material had high viscosity, similar to that of cold molasses. This phenomenon also happened to a smaller extent between the panels, after they buckled and broke loose from the fixture. The two parallel panels became fused together when extinguishing agent (Fig. 7b) was applied to them.

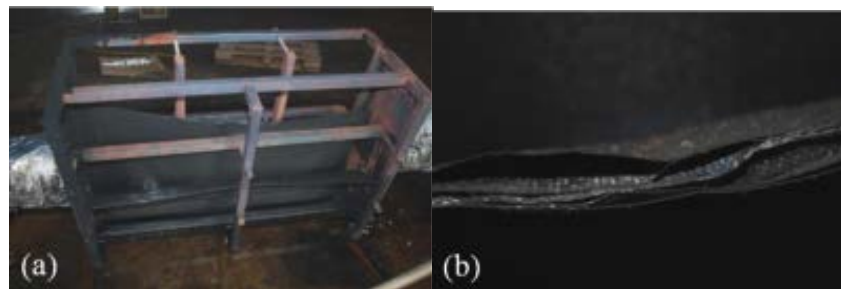


Figure 6. (a) Burned and Buckled Composite Panels in Test Fixture; (b) Delamination of Composite Laminate Layers

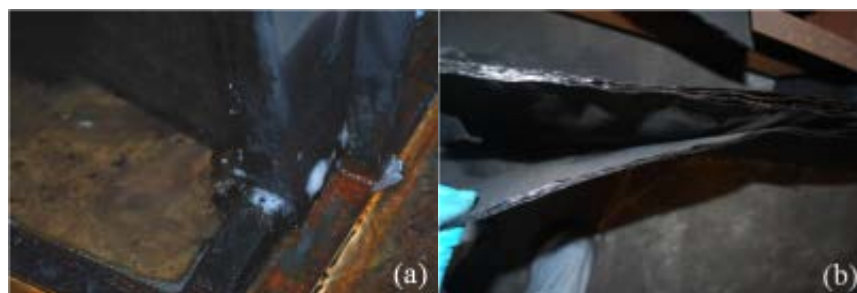


Figure 7. (a) Composite Resin Resolidified on Test Fixture Following Extinguishment; (b) Fusion of Composite Panels

Figure 8 shows representative data (temperature and total heat flux) for two different technologies, AA and UHP. Once pool extinguishment commences (red box), the temperature increases as the pool fire becomes more turbulent. Composite extinguishment begins (green diamond) following a peak in temperature and while heat flux is significantly reduced. When the composite and pool are extinguished (yellow triangle), the temperature can remain high but will gradually decrease following extinguishment.

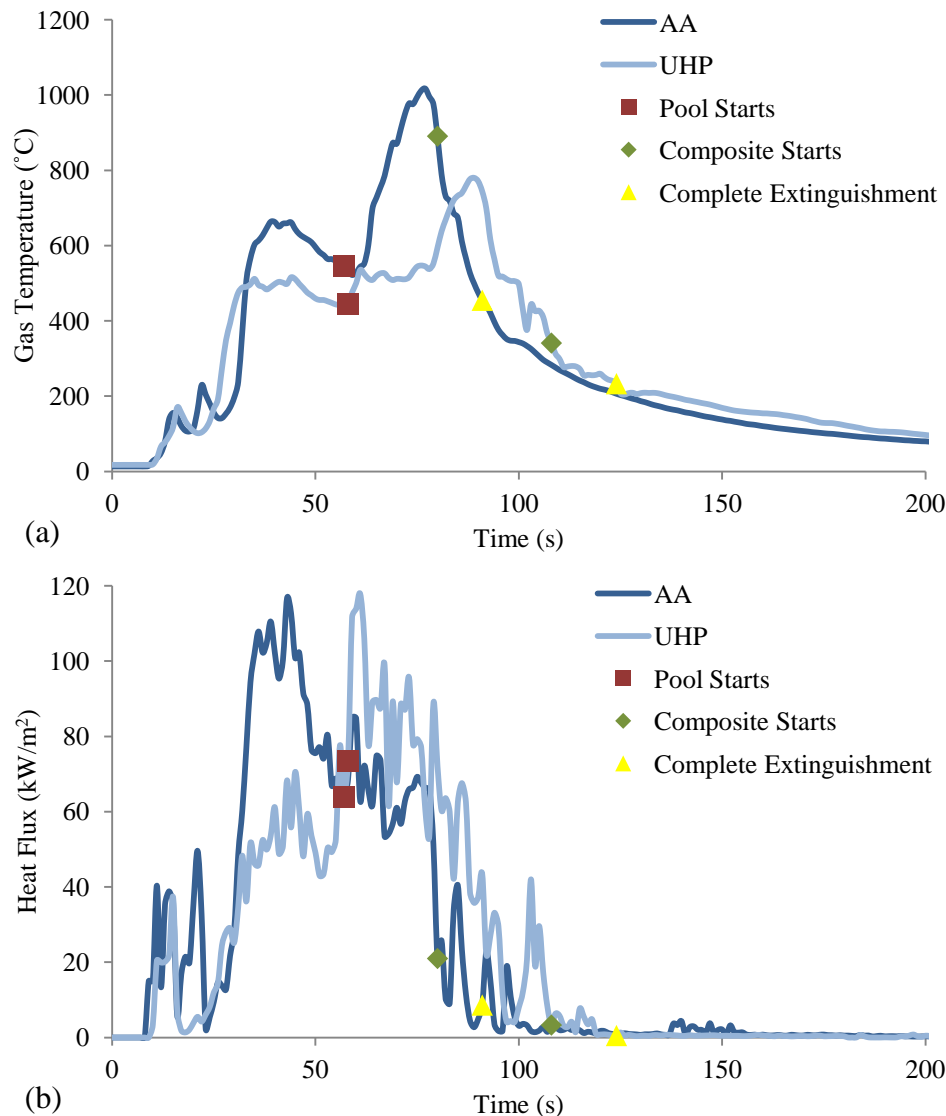


Figure 8. (a) Temperature and (b) Total Heat Flux for Representative AA and UHP Test Runs

4.1.1. Preparatory Tests

Most of the preparatory tests were performed to determine optimum parameters under which subsequent tests would be run. Some tests were conducted to give the firefighter experience and to establish a technique to extinguish both the pool and composite fire. The main parameters investigated that affected the intensity and the possibility of reignition of the composite fire were

the duration of pre-burn (varied from 40 s to 3 min) and the distance from the bottom of the tilted (higher) composite panel to the fuel level (varied from -0.5 cm [-0.2 in] [tilted panel also dipped in fuel] to 6.4 cm [2.5 in]).

Nine carbon-epoxy and two carbon-BMI panel sets were used in preliminary burn tests. The first test was performed with a 3-min pre-burn, which completely delaminated the carbon-epoxy material. As no resin remained within the sample, the pre-burn time was scaled back to 40 s, 1 min, and 1 min 20 sec. For the carbon-epoxy panels a pre-burn time of 1 min was found to be sufficient to heat the composite, yet still have resin remaining following extinguishment to allow for the possibility of reignition. However, upon testing the carbon-BMI samples, which were half as thick as the epoxy panels, it was determined that a pre-burn time of 45 s should be used for subsequent testing.

In addition to the pre-burn duration, the effect of the distance from the tilted panel to the JP-8 fuel level (air gap) was also investigated. It was found that a larger air gap allowed more air into the cavity, which increased the burning rate of the composite material through convection. Although desirable for the purposes of showing the difficulty to extinguish the composite fire, an overly wide air gap limited the time available for the firefighter to put out the composite fire while the composite still contained resin. An air gap of 1 in gave relatively consistent heat flux levels as well as adequate amounts of remaining resin after extinguishment.

After tilt effects were determined (see section 3.1.4), various application technologies were tested. The UHP technology was significantly different from all other systems, having much higher pressure and velocity of delivery. The velocity of the UHP system required the firefighter to attack the fire from a position approximately 3 m (10 ft) from the pan, whereas other systems could be attacked near the rim of the pan. This technology also limited the way the agent was applied to the fire. As it was nearly impossible to apply agent to only the pool fire first and then the composite fire, it was decided that agent application would be directed to the pool first, allowing some of the agent to hit the composite panels and some to fall outside the pool, which in some cases was a significant amount (Fig. 9). Once the pool was extinguished, the firefighter focused on the composite cavity. For these reasons, the firefighter practiced (two test runs) with the UHP system on plywood panels in a configuration similar to the composite panels, and determined how best to extinguish the fire.

To understand how composite materials reacted to the JP-8 pool fire, two tests were performed wherein 18.9 L (5 gal) of JP-8 was put in the pan and allowed to burn to completion (i.e., no extinguishment), burning the composite panels in the metal fixture. After the pool fire had self-extinguished from lack of fuel, the buckled and delaminated composite material continued to burn. The flame observed from the composites was a small, laminar flame, similar to a candle. In one test, the flame burned for 13–15 min after the pool self-extinguished. The composite panel had buckled, and had partially fallen into the water, creating an enclosed air pocket that ran the length of the panel between the buckled composite and the remaining water in the pan (Fig. 10). The flame was observed to transition from one side of the panel to the other side multiple times, traveling through this air pocket accompanied by a soft popping sound, and continued burning on the other side of the panel. Slight variations of pressure (e.g. wind) appeared to affect the transfer of volatiles through an air pocket created by the buckled composites.



Figure 9. Photograph Following UHP Extinguishment, Showing Significant Amounts of Agent That Did Not Land on the Pool and Composite Fire

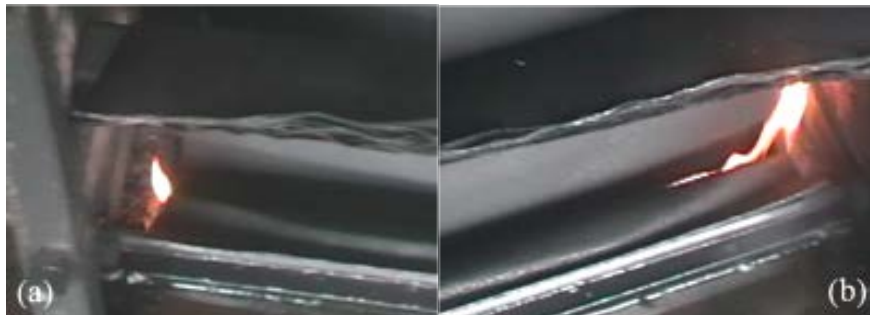


Figure 10. Frames Showing Laminar Flame from Burning Composite—in (a) the Right Side [Not Shown] Is Not Burning; (b) Approximately 10 s Later the Flame Transitioned through the Air Gap from the Left Side [Not Shown] to the Right

This local reignition and flame transition could have been caused by a couple of phenomena. First, because the buckled composite was partially submerged in the water, it is probable that not all of the resin matrix was consumed in the pool fire alone. However portions of the insulating composite were still hot (i.e., those sections not submerged in water), allowing for pyrolysis and volatilization of the resin and continued flaming combustion. Second, because the panel had delaminated, JP-8 could have migrated from the pool into the interior of the composite via the thin fibers (i.e., wicking). This stored fuel could have then volatilized and continued to burn for some time after the original JP-8 pool had self-extinguished.

4.1.2. Tilt Effects

The first set of actual experiments was designed to determine the effects of tilt on burning and extinguishment in the standard test as discussed above. Data were recorded and analyzed, and no significant difference in extinguishment times was found between positive and negative tilt directions (Fig. 11a). Error bars on all figures show 85% confidence intervals. The only

significant difference between positive and negative tilt directions was the amount of total heat flux measured in the cavity, the positive tilt direction having a higher total heat flux during pre-burn (Fig. 11b). Because of the fixture design, in the negative tilt direction a metal bar somewhat restricts influx of air in the chimney, slowing down convective heating through the cavity and ultimately slowing down burning. Because this was observed only during the pre-burn period, and because the slower heating rate would retain resin in the thin panels (allowing for possible reignition), the negative tilt direction was selected for use in all subsequent tests.

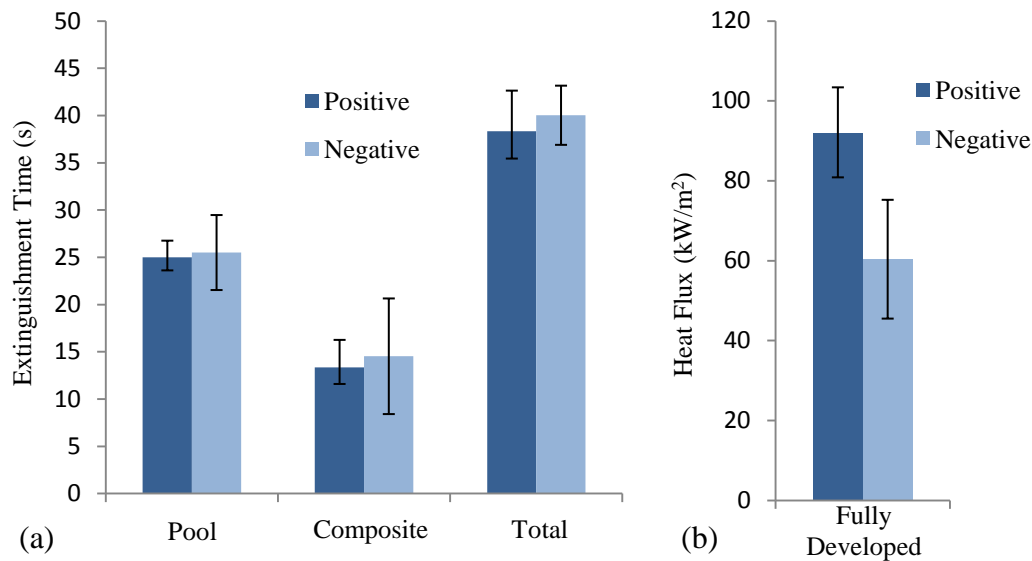


Figure 11. Positive and Negative Tilt Results: (a) Average Extinguishment Times; (b) Average Heat Flux during Pre-burn after the Pool Fire was Fully Developed

4.1.3. Technology Effects

Once the tilt effects had been determined, the second set of experiments tested the effectiveness of various technologies on the standard test as discussed above. Extinguishment times are shown in Fig. 12a. AA and CAF systems performed essentially the same for extinguishment in this fire test, whereas the NAA system required nearly twice as long to extinguish the fire. UHP performed better than NAA, but poorer than AA and CAF. The UHP system created significantly more momentum than did the other systems. This required fighting the fire at a greater distance than for the other methods, as the momentum would blow the fuel from the pan, creating large fireballs. Fighting fires from a distance limited the amount of agent that could be applied directly to the pan and on the composites, because significant quantities of agent (estimated 1/3 of total) fell on the floor. Heat flux measured in the chimney at the time of pool extinguishment and total extinguishment, showed similar heating rates for all the different technologies (see Fig. 12b). Therefore, this experiment was inconclusive regarding selecting an optimum technology based on heat flux alone. Total extinguishment time was the only statistically significant difference among the various technologies, which would narrow the field down to AA and CAF, which had the fastest extinguishment. As AA is the current standard technology and would follow the original MIL-SPEC standard^[3] more closely, AA was selected for use in all subsequent tests.

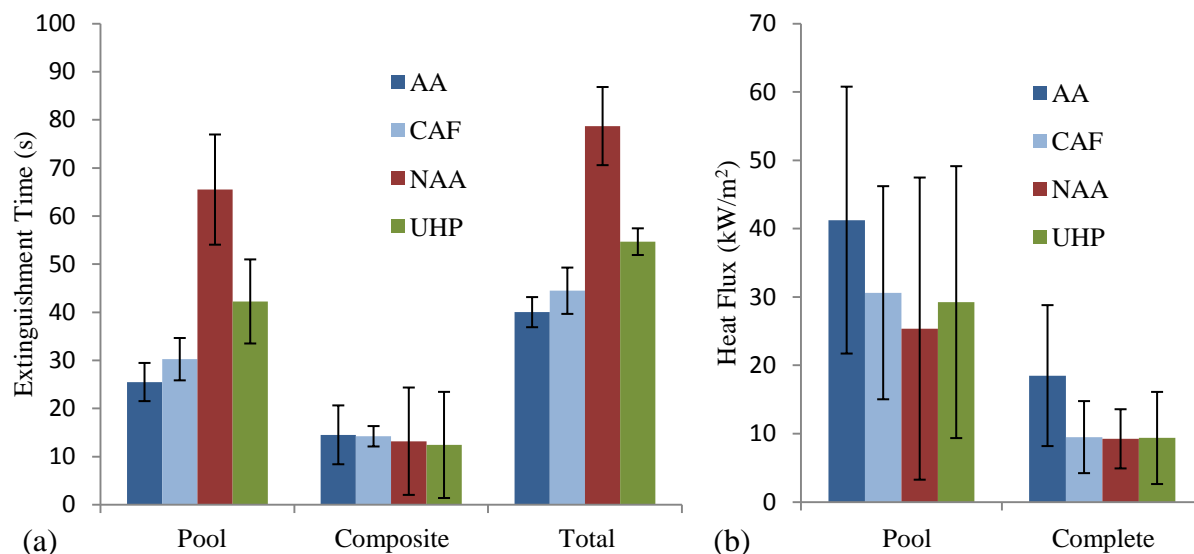


Figure 12. Various Technology Results: (a) Average Extinguishment Times; (b) Average Heat Flux at the Time of Pool and Complete Extinguishment

It should be noted that though UHP did not perform exceptionally for this specific test, it could still be a sound option for composite extinguishment. As discussed above, in this intermediate scale test the UHP system blew fuel from the pan, making it difficult to extinguish the pool fire. UHP has shown excellent results on large-scale JP-8 pool fires^[6] so, for a large-scale fire, the pool would not be as difficult to extinguish. Also, optimum flow conditions, particularly foam expansion ratio, would be desirable for a representative intermediate-scale test and would be the subject for further investigation.

4.1.4. Agent Effects

After technology effects were analyzed, the final set of experiments tested the effectiveness of various agents on the standard test as discussed above. As AFFF was used on all pool fires during this set of experiments, extinguishment times for the composite material are shown in Figure 13a only for the secondary agents. Extinguishment times for the water-based agents AFFF, FFFP and Class A were similar (approximately 18 s), but extinguishment by PKP was significantly faster. However, PKP did not cool the composite material as well as the water-based agents. An example of this is given in Figure 13b, which shows that composites experienced significantly higher heat flux inside the cavity after application of PKP than of other water-based agents. The higher heat flux intensity ($\sim 14 \text{ kW/m}^2$) can cause reignition.

Gas temperatures when PKP was applied did not significantly differ from AFFF and Class A foam (Fig. 13c) at extinguishment, but the water-based agents FFFP and HG caused temperatures at least 100°C lower at 80 s, and 50°C lower for more than 5 min (Fig. 14). Notice also that extinguishment temperatures after application of PKP and of Class A foam were similar, but the foam caused faster cooling and reached temperatures similar to those of the other water-based agents within 3 min following extinguishment. These temperature differences between PKP and water-based agent application were also verified when a hand-held IR thermometer

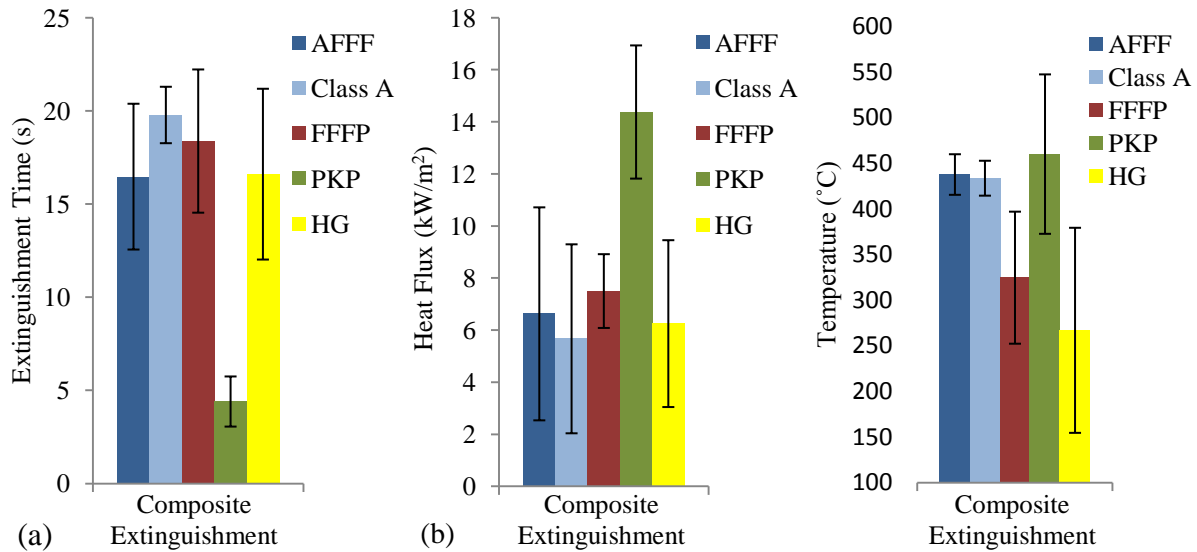


Figure 13. Average Values at Composite Extinguishment of (a) Times, (b) Heat Fluxes, and (c) Temperatures of the Various Agents

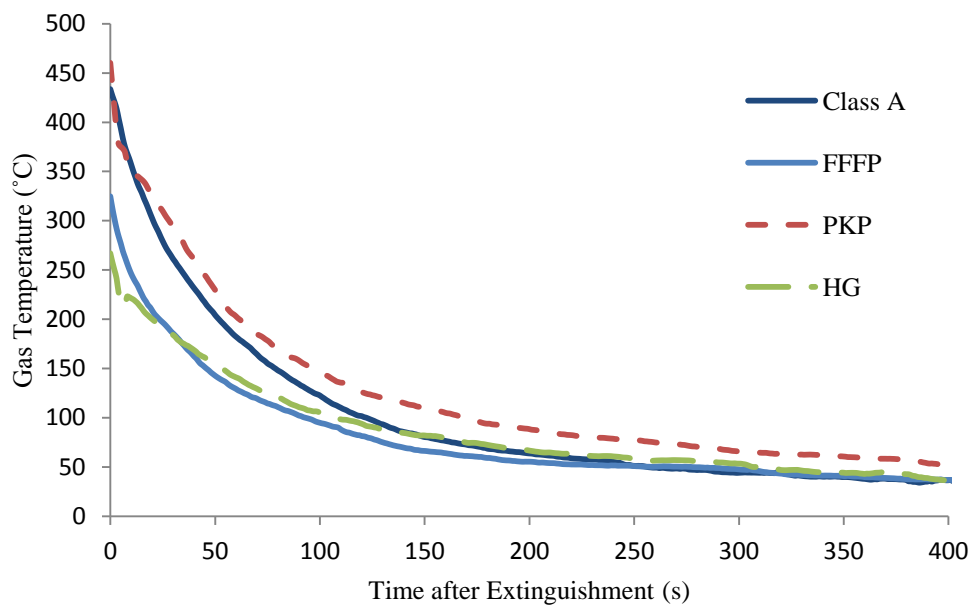


Figure 14. Gas Temperature Values Recorded for Various Secondary Agents Following Extinguishment

measured surface temperatures. Five min after extinguishment, the temperature of panels extinguished with PKP was approximately 170 °C and of panels extinguished with Class A foam approximately 90 °C. Composites extinguished with PKP were also observed to reignite about 4 s after primary extinguishment (Fig. 15). This inability of PKP to cool the composite limits its usefulness for use as the only agent to extinguish composite material.



Figure 15. Sequence Showing Extinguishment Using PKP and Reignition at 7.5 s

That composites are good insulators is a drawback when trying to extinguish a composite fire after the material has undergone significant heating. This is even more challenging when the composite material delaminates, which drastically reduces its thermal conductivity and limits its cooling rate. HG was chosen as a candidate agent primarily because of its ability to stick to the solid surface and provide sustained cooling, whereas other water-based agents flow off or evaporate from the solid surface. It can be seen in Figure 13c that the temperature at the time of composite extinguishment was significantly lower when HG was used than for the other agents (excluding FFFP), and that HG provided continued cooling after extinguishment (Fig. 14).

However, some problems with the HG agent arose during the experiments. First, HG was found to sputter as it leaves the nozzle, which created inconsistencies of application on the composite surface. This likely can be eliminated by using customized equipment, as the MIL-SPEC nozzle was designed for foam, not gel. This sputtering also caused the foam layer that had already been applied to the pool to break up, which, in some cases, allowed the pool to reignite, hindering the effectiveness of the HG agent. After the fire is extinguished using AFFF, HG may be used to coat all surfaces to provide prolonged cooling to the composite material and inhibit heterogeneous oxidation of the remaining carbon fiber from the air. Both of these properties of HG will contribute to inhibiting reignition of the composite material.

4.2. Small-Scale Experiments

Qualitative results of the small-scale experiments showed that samples ignited with the aid of the direct-impingement propane burner about 5–10 s after heating began (Fig. 16a). This sample continued to burn primarily on the heated side throughout the pre-burn time (1 min), although some flame transitioned to the back side. Once the burner was removed, the flame self-



Figure 16. (a) Burning Small-scale Composite Sample; (b) Pockets of Black Liquid That Formed on the Composite Surface after Burning

extinguished within 5 s during tests with no agent application. Small-scale experiments showed qualitative post-combustion properties similar to those from intermediate-scale experiments. For agent tests, the flames were extinguished when agent was applied (within 1 s after burner removal). Where the propane flame impinged on composite sample, a circular region of delaminated fiber remained, thickness in this region increasing up to twice the original dimension. Also following burner removal, small pockets of black liquid formed on the surface, which was assumed to be matrix or residual tar that seeped out of the interior composite sample (Fig. 16b).

While the propane burner was applied to the composite sample, the temperature of the back side increased linearly for about 40 s then leveled off for the next 20 s of the pre-burn period; Figure 17 gives a representative temperature profile during heating. When the heat source is removed, the temperature gradually decreases for all application configurations, though the rate at which the composite cools varied for each one. This process is portrayed in Figure 18, which shows the IR temperature measured on the back side of the composite. AFFF cooled the

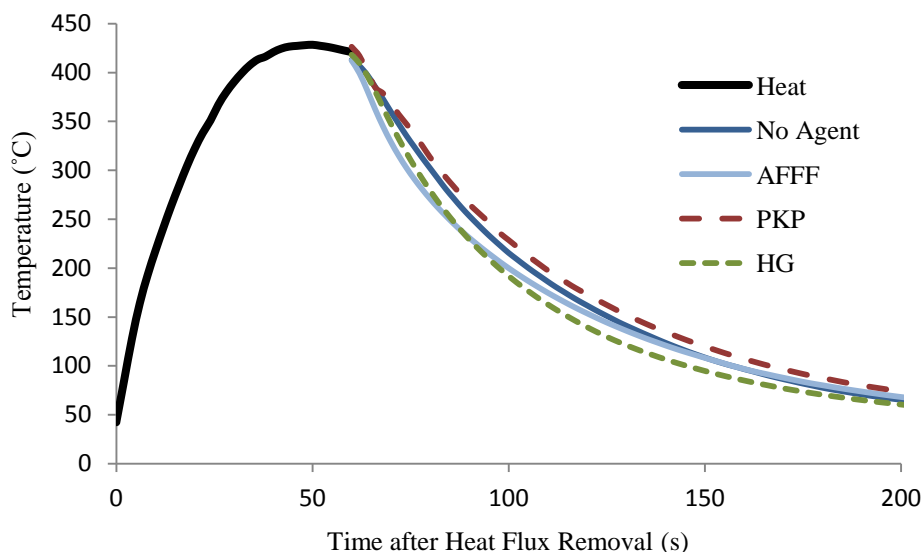


Figure 17. Back Side Temperature Profiles of Small-scale Composite Panels Both before and after the Heat Source was Removed and Agent Applied

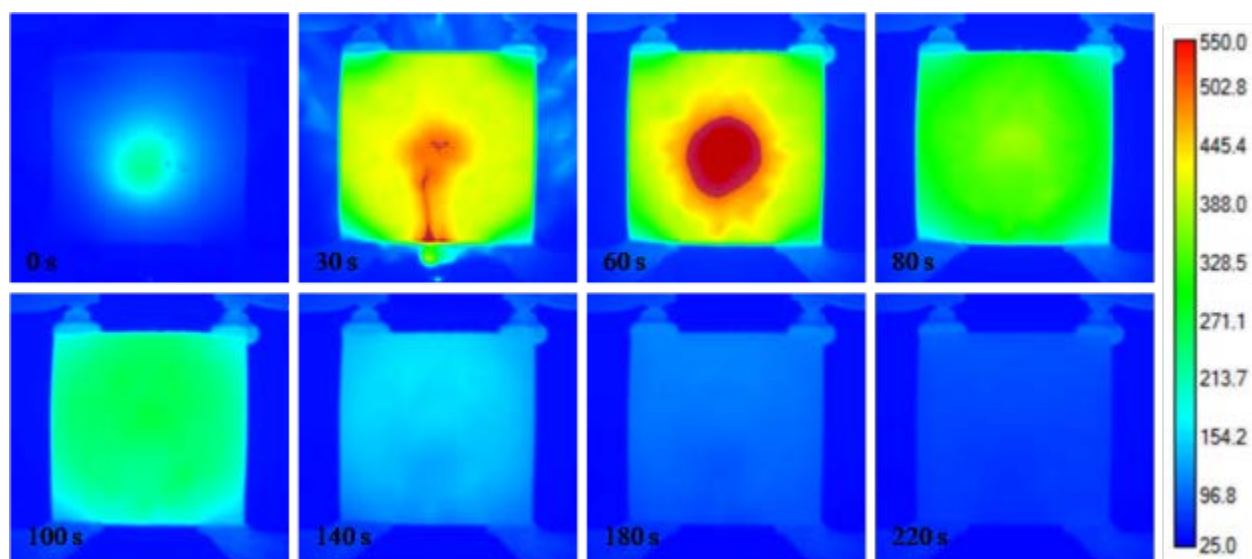


Figure 18. IR Temperature Sequence of a Composite Sample Being Heated and Subsequently Cooled (Starting at 60 s) in Ambient Air

composite most quickly within the first 20 s, presumably by penetration into the sample and water removing heat from the sample. However, the rate at which the composite cooled was not maintained for as long as for HG, and the sample stabilized at a temperature similar to tests in which no agent was applied. As HG remained on the composite surface it allowed prolonged cooling of the composite. At 20–40 s after burner removal, the temperature was about 35 °C below that for PKP and 25 °C below that after no agent application. It was also noteworthy that the composite, after application of PKP, showed slightly higher temperatures (by 5–10 °C) than after no agent application, presumably due to a layer of insulating powder that caked onto the solid surface, inhibiting cooling of the composite material.

4.3. Agent Cost Analysis

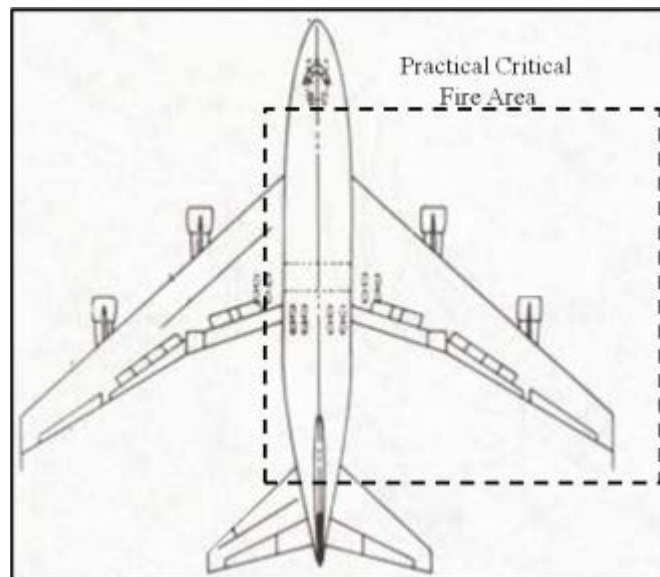
For a more thorough understanding of the feasibility of the various agents for composite firefighting, a quick cost analysis was performed. Manufacturer bulk costs (2010 dollars) per effective volume for each of the agents used in this study are displayed in Table 3. Effective volume is defined as either the volume of water and foam concentrate, the equivalent PKP amount based on flow rates for large-scale systems as shown in section 3.1.5 (i.e., 0.45 kg [1 lb] PKP is equivalent to 0.5 L [0.13 gal] of AFFF and water), or the HG volume produced after mixing the powder and water (e.g., 0.45 kg [1 lb] powder yields 76 L [20 gal]). Also included in the table are flow requirements or estimates for each agent, which gives a corresponding flow rate cost. These costs do not include the price of water.

The cheapest agent, primarily because it is mostly water, is Class A foam, which constitutes 0.5% by volume of the total agent. It is not typically used on aircraft fires so no flow rate is specified^[2] in NFPA 403, and its fire performance on Class B fuels is not acceptable. AFFF is slightly cheaper than FFFP, but also has a lower flow requirement, giving a savings over FFFP of nearly 50%. PKP is currently used as a complementary agent, and thus its required flow rate is

Table 3. Cost Comparison for Various Fire Suppression Agents

Agent	Cost (\$/L [\$ /gal])	Flow Requirement (L/min/m ² [gal/min/ft ²])	Flow Cost (\$/min/m ² [\$ /min/ft ²])
AFFF	\$0.12 [\$0.47]	5.5 [0.13] ^α	\$0.66 [0.06]
FFFP	\$0.15 [\$0.58]	7.5 [0.18] ^α	\$1.13 [0.11]
Class A	\$0.01 [\$0.05]	NA	NA
PKP ^β	\$2.73 [\$10.35]	0.17 [0.004] ^γ	\$0.46 [0.04]
HG	\$0.20 [\$0.75]	6.5 [0.16] ^δ	\$1.30 [0.12]
^α – as prescribed ^[2] by NFPA 403 ^β – 0.45 kg (1 lb) PKP is equivalent to 0.5 L (0.13 gal) AFFF and water ^γ – assumed 4.5 kg/s (10 lb/s) flow rate with a practical critical fire area of 1800 m ² (19,400 ft ²): Category 9 Airport ^[2] ^δ – estimated value. Not an actual requirement.			

lower. The bulk cost is initially high, but because so little agent is used, the overall cost is cheaper than for AFFF alone. HG is comparable in bulk price to other water-based agents, though the flow rate requirement is largely unknown because the agent is relatively new. Table 3 estimates a flow requirement of 6.5 L/min/m² (0.16 gal/min/ft²), which assumes that HG alone would be used as the primary agent (as AFFF is). If HG were used as a secondary agent (as PKP is) the flow requirement would undoubtedly be lower. Only about 50% of the practical critical fire area (PCA) as defined^[2] by NFPA 403 (Fig. 19) is actual airplane. The other 50% is possible fuel spill area surrounding the wing. As a secondary agent, HG would be used only on the aircraft itself, thus reducing the amount of agent applied to the composite aircraft and lowering the overall cost, possibly by half. As HG provides sustained cooling (i.e., sticks) to the surface of the aircraft, the need for continual application of AFFF would be reduced, as was observed in the 2008 Anderson B-2 incident.

**Figure 19. Schematic Showing Practical Critical Fire Area^[2] Defined by NFPA 403**

5. CONCLUSIONS

A robust intermediate-scale test standard was developed to determine the effectiveness of various technologies (AA, NAA, CAF, and UHP) and agents (AFFF, FFFP, Class A, PKP, and HG) on composite materials. Here are significant findings from these tests:

- AA and CAF systems achieved faster extinguishment than UHP and NAA.
- For this test standard, UHP effectiveness was limited because the force of its directly applied scatters the pool fire—which is not an issue in a large-scale fire. In the test, delivery from 10 ft away caused a significant amount of agent to miss the target pool and composite fire.
- PKP extinguished the composite material fire most quickly, but provided little post-extinguishment cooling, allowing for reignition of the solid material.
- Water-based agents (AFFF, FFFP and Class A) all had similar extinguishment times.
- HG cooled the composite, but disturbed the foam blanket covering the extinguish pool, allowing the JP-8 fuel to reignite.

In addition to these intermediate-scale tests, another series of small-scale samples were tested to determine the cooling effectiveness of various agents (No Agent, AFFF, PKP and HG). Three significant findings were made from this test series:

- HG stuck to the composite surface and provided continued cooling.
- AFFF cooled the composite initially, but did not maintain its cooling effectiveness as long as HG. The water dripped or evaporated from the surface, so continuing heat removal would require repeated applications.
- PKP formed a layer of insulating powder on the surface, which inhibited cooling—even compared to no agent applied to the composite.

A simple cost analysis performed to discuss the feasibility of using the various agents used in these tests was based primarily on requirements^[2] from NFPA 403. Results are shown here:

- Class A's cost per volume of agent was the cheapest, though its effectiveness as a primary agent on Class B aircraft fires is questionable.
- AFFF costs roughly half as much as FFFP for an aircraft fire.
- Since PKP is a complementary agent, the amount and total cost of the agent would be about 30% lower than the cost of AFFF, though both would be required on a fire truck.
- As a primary agent HG was estimated to cost twice as much as AFFF; applying HG as a secondary treatment would consume significantly less agent, lowering its overall cost.

6. RECOMMENDATIONS

This study of the effectiveness of extinguishment of composite fires by various types of technologies and agents answered many questions. Following is a list of recommendations that could be considered for extinguishing a composite fire:

- AA should be used to extinguish the composite fire based on these test results.
- Future or up-and-coming technology (e.g., UHP) has potential to be used on large-scale composite fires. The standard used in this test series was not ideal for UHP, but UHP still has significant potential for use on composite fires. Further tests are recommended to determine optimum parameters (i.e. flow rates, scaling, appropriate nozzle, expansion ratio, etc.).
- AFFF should be used as a primary agent to extinguish fires, based on both effectiveness and cost.
- Secondary agents could also be used to effectively extinguish a composite fire:
 - PKP can be used in coordination with AFFF, but should not be relied on as a primary agent because it does not cool the composite material, which allows for reignition.
 - HG can be applied to the composite surface after the initial fire (particularly a JP-8 fueled fire) is extinguished. HG sticks to the composite, which allows for continued cooling and inhibits transport of oxygen to the solid, both of which will limit the possibility of reignition. Further tests are recommended to clarify optimum use of HG.

These experiments also spawned various questions that could lead to further research in the area of composite fire, including

- What is the mechanism of reignition?
- What is the interaction between fuel and burning, delaminated composite? How much fuel can it wick up into its interior?
- How could these tests be used for large-scale applications?
- How are these composites affected under high heat-flux conditions?
- What is the effect of stress on a burning composite with regards to structural failure?
- What is the compatibility of HG when used as a secondary agent to AFFF?

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APPENDIX

The following tables give raw measurement data for the various experiments performed on BMI/carbon fiber panels using the standard test protocol developed. See Section 3 for details.

Data showing effects of tilt using an AA system with AFFF.

Tilt ($\pm 15^\circ$)	Time (s)			Temperature ($^\circ\text{C}$)		Heat Flux (kW/m^2)	
	Pool Ext.	Comp. Ext.	Total Ext.	Pool Ext.	Total Ext.	Pool Ext.	Total Ext.
+	23	11	34.0	838.9	272.1	30.0	13.0
	27	13	40.4	644.8	277.4	38.5	2.5
	24	11	35.4	NA	NA	56.5	21.0
	26	18	43.6	NA	NA	76.0	18.5
-	23	18	41.0	671.6	448.8	32.5	7.5
	29	13	42.2	NA	NA	33.0	23.5
	21	21	41.7	NA	NA	71.5	12.0
	29	6	35.2	NA	NA	28.0	31.0

Data showing effects of various technologies using AFFF.

Technology	Time (s)			Temperature (°C)		Heat Flux (kW/m ²)	
	Pool Ext.	Comp. Ext.	Total Ext.	Pool Ext.	Total Ext.	Pool Ext.	Total Ext.
AA	23	18	41.0	671.6	448.8	32.5	7.5
	29	13	42.2	NA	NA	33.0	23.5
	21	21	41.7	NA	NA	71.5	12.0
	29	6	35.2	NA	NA	28.0	31.0
CAF	35	12	47.3	623.0	525.6	17	6.5
	28	17	44.6	NA	NA	17	8.5
	25	12	37.4	NA	NA	39.5	5.5
	33	16	48.6	NA	NA	49	17.5
NAA	56	30	85.8	737.4	483.5	59.5	15.0
	55	12	66.5	732.2	400.2	16.5	9.0
	72	8	80.4	619.7	550.8	16.0	9.0
	79	3	82.1	386.8	364.7	9.5	4.0
UHP	32	24	55.8	671.6	448.8	33.5	6.5
	51	16	66.7	NA	NA	54.0	10.5
	52	5	57.1	NA	NA	4.0	2.0
	34	5	39.1	NA	NA	25.5	18.5

Data showing effects of secondary agents using an AA system with AFFF used on the pool.

Agent	Time (s)			Temperature (°C)		Heat Flux (kW/m ²)	
	Pool Ext.	Comp. Ext.	Total Ext.	Pool Ext.	Comp. Ext.	Total Ext.	Pool Ext.
AFFF	NA	NA	141.0	NA	416.0	NA	7.0
	37	19	56.0	748.5	467.3	36.0	9.5
	35	13	48.2	692.4	444.6	36.5	0.5
	45	17	62.2	746.8	423.2	52.5	9.5
Class A	48	22	69.9	NA	NA	NA	NA
	48	20	67.5	836.6	427.0	39.0	3.0
	45	18	63.1	840.4	423.8	33.0	5.5
	44	20	63.6	797.3	450.4	41.5	8.5
FFFP	43	14	57.4	750.4	375.0	43.5	5.5
	41	18	59.0	731.6	333.0	44.5	7.5
	39	24	62.9	NA	NA	51.5	8.0
	43	17	60.2	635.4	266.1	33.0	9.0
PKP	46	4	50.2	521.2	394.1	18.5	13.0
	42	5	47.4	483.6	410.5	14.5	11.5
	46	6	51.5	630.4	443.1	22.0	15.5
	44	3	46.5	721.0	593.0	68.5	17.5
HG	40	NA	NA	689.1	310.6	27.5	3.5
	NA	17.7	NA	685.3	313.3	43.5	11
	71	15.5	86.5	431	350.2	13.0	6.0
	41	NA	NA	590.3	93.8	35.5	4.5

LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS

AA	air-aspirated
ACC	Air Combat Command
AFB	Air Force Base
AFCESA	Air Force Civil Engineer Support Agency
AFFF	aqueous film-forming foam
AFRL	Air Force Research Laboratory
BMI	bismaleimide
CAF	compressed-air foam
FFFP	film-forming fluoroprotein
gpm	flow rate of gallons per minute or gal/min
HG	fire suppression hydrogel
IR	infrared
JP-8	currently used jet fuel
MIL-SPEC	military specification as used in MIL-F-24835F
NAA	non-air-aspirated
NFPA	National Fire Protection Association
PKP	potassium bicarbonate (Purple K) dry chemical
RAF	Royal Air Force (UK)
UHP	ultra-high pressure
USAF	United States Air Force
USN	United State Navy